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Spectral analysis of gas-dynamic processes in the intake system of a supercharged piston engine

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Abstract. The study of gas-dynamic processes in gas-air systems of engines in order to improve the processes of gas exchange, mixture formation and combustion is an urgent task. The results of experimental studies of gas-dynamic processes in the intake system of an engine with turbo-compressor are presented in the article. A brief description of the setup and methods of experiments is presented. A spectral analysis of functions was chosen as a tool for monitoring gas-dynamic phenomena in different systems. A comparative analysis of the amplitude spectra of the pulsations of the velocity and pressure of the flows in the intake system of the engine with and without a turbo-compressor is presented in the article. The installation of a turbo-compressor leads to a significant change in the structure of gas flows in the intake system. A method for stabilizing the pulsating flow in the intake system by installing a leveling grid in the output channel of the compressor is proposed. It has been established that the presence of a leveling grid in the intake system of an engine with turbo-compressor leads to a decrease in the low-frequency amplitudes of the velocity pulsations and the pressure of the flow by up to 30%.

1. Introduction

The gas-dynamic perfection of the intake and exhaust systems of piston internal combustion engine (PICE) largely determines the quality of the gas exchange processes, as well as the phenomena of mixing fuel and air and their subsequent ignition [1-3]. The presence of large-scale or small-scale turbulent vortices has a significant impact on the hydrodynamic resistance of the intake duct. And the turbulence level of the working fluid in the cylinder of the PICE determines the conditions for mixing air and fuel [4, 5]. A large number of scientific works are devoted to the study of the flow structure in gas-air systems of engines with and without turbo-compressor (TC) based on numerical simulation of flows [6-8]. Physical and mathematical modelling is usually performed for stationary gas flows, but there are studies for pulsating flows [9, 10]. Also, experimental studies of the flow structure in the systems under consideration using optical methods (by the high-speed PIV-method) have been carried out in recent years [11-13]. In most cases these studies provide only a visual picture of the flow structure, on the basis of which one can only assume the scale of turbulence in ducts and engine cylinder. The installation of a turbo-compressor leads to a significant change in the gas-dynamic phenomenas in the gas-air systems of PICEs [14, 15]. Estimation of the degree of influence of the blade apparatus of the TC compressor on the structure and scale of the turbulence of pulsating flows in the intake system of a PICE is an urgent task. It is possible to predict the level of turbulent vortices in gas-air systems at the design stage of engines based on the spectral analysis of periodic functions of velocity and pressure of the flows.

The main purpose of this article is to conduct a comparative analysis of the spectra of the gas-dynamic characteristics of the flows in the intake systems of PICEs with and without turbo-compressor, as well as to assess the influence degree of the turbo-compressor on the flow structure in such systems.

2. Experimental base and formulation of the research task

The studies were carried out on an experimental stand consisting of a single-cylinder PICE (cylinder diameter of 82 mm, piston stroke of 71 mm) with a turbo-compressor TKR6. An electric drive with a frequency converter was used to rotate the crankshaft. The studies were conducted without fuel combustion. The variation range of the crankshaft rotational speed n of PICE ranged from 600 to 3,000 rpm. The turbo-compressor rotor was rotated by supplying compressed air to the blades of the turbo-compressor turbine from an external source. The turbo-compressor rotor speed n_{TC} varied from 20,000 to 60,000 rpm. The operating modes of the engine and the turbo-compressor were selected based on the coordination of the air flow through the PICE cylinders and the turbo-compressor performance. The range of n and n_{TC} is planned to be expanded in further studies. The configuration of the intake system was as follows: the duct length was 300 mm, the length of the compressor outlet channel was 150 mm, the internal diameter of the channels was 32 mm. The studied intake system was without a charge air cooler. The control section with sensors was located at a distance of 150 mm from the input window of the cylinder head. Air with a temperature of 20-25°C (engine without TC) and with a temperature of 35-45°C (PICE with TC) was used as the working medium.

In this work, studies of gas flows in the intake system of PICE were carried out taking into account the gas-dynamic nonstationarity [16]. At the first stage of research, gas-dynamics of flows in the hydraulic system of a PICE without a turbo-compressor was studied. In this case, the physical mechanism of air movement is a vacuum wave in the engine cylinder. At the second stage, gas-dynamics of the flows in the hydraulic system of a PICE with turbo-compressor was studied. In this case, the physical mechanism of air movement changes: the source of movement is already the compression waves after the turbo-compressor (overpressure). Moreover, the blade unit of the TC centrifugal compressor has a mechanical effect on the pulsating air flow in the hydraulic system. According to the authors, this should lead to a significant change in the structure and gas-dynamic parameters of the air flow. At the third stage, the method of stabilization of pulsating gas flows in the hydraulic system by installing a leveling grid (honeycomb principle) in the output channel of the TC compressor was proposed. This principle is often used in the field of fluid dynamics to control the properties of gas flows.

The spectral analysis of functions is a universal tool for scientists in the analysis of gas-dynamic phenomena in hydraulic systems. The spectral analysis of functions $w_x = f(\tau)$ and $p_x = f(\tau)$ was carried out in the PowerGraph program using the fast Fourier transform algorithm. The characteristics of the spectrum were: 1) the type of spectrum was the amplitude spectrum; 2) the number of values during the fast Fourier transform was 1048576; 3) the type of weight function was triangular. The spectral analysis of harmonic functions of the velocity and pressure of flows is a classical approach for studying the flow characteristics under different boundary conditions.

The instantaneous values of the air flow velocity, average over the cross section, w_x and the instantaneous values of the static pressure p_x in the intake duct were determined. A constant-temperature hot-wire anemometer was used to determine w_x. The speed of the hot-wire anemometer was 2 ms. The pressure sensor was used to determine the pressure p_x in the duct (the speed was 1 ms). For a more detailed measurement system, see [17].

3. Research results and discussion

The change in flow velocity w_x and pressure p_x over time in the intake system during the duty cycle of a PICE with and without a turbo-compressor is shown in figure 1. Data for different modes of turbo-compressor operation and different configurations of the hydraulic system (with and without the levelling grid) are shown. It can be seen in figure 1 that the presence of a turbo-compressor in the intake system of the PICE leads to noticeable changes in the function $w_x = f(\tau)$ both during the intake process and during the closed valve (figure 1, *a*). It can be noted that the maximum values of the air flow velocity are increased (by about 10-15%), and as well as more pronounced oscillatory phenomena of the air flow velocity in the intake duct during the entire engine operating cycle are observed. It can be assumed that they are associated with the influence of the blade apparatus of the TC centrifugal compressor, which is the source of external turbulence for the pulsating flow in the hydraulic system. The type of curve $p_x = f(\tau)$ depends essentially on the presence or absence of a turbo-compressor in the hydraulic system (figure 1, *b*). There is smoothing of pressure pulsations in the hydraulic system of the PICE with turbo-compressor, as well as an increase in the average pressure value during the working cycle.

A spectral analysis of these functions was performed to obtain detailed information about the gas flow. Spectral analysis was performed at a fixed operating mode of the installation (n and $n_{\text{тс}}$ were constant). At least 50 duty cycles participated in spectral analysis. Spectrum amplitude graphs for the function $w_x = f(\tau)$ for turbocharged and non-turbocharged PICEs are shown in figure 2.

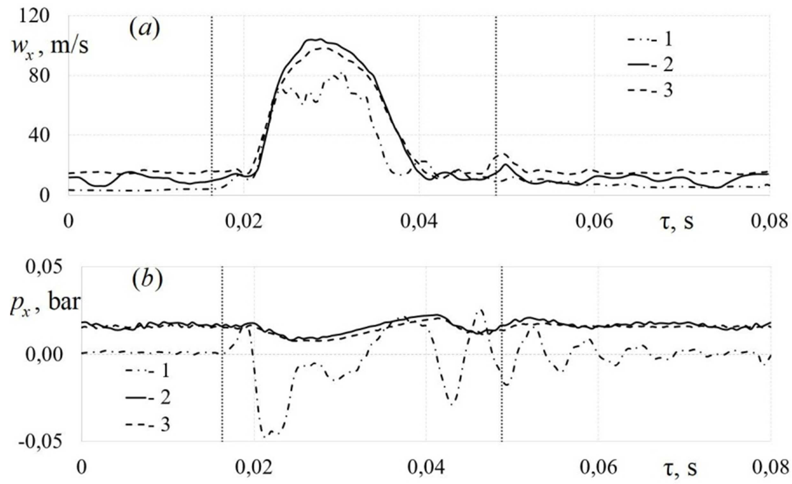

Figure 1. Dependences of local velocity w_x (*a*) and pressure p_x (*b*) of air flow on time in intake systems of piston engines under different conditions: 1 – PICE without turbo-compressor at n = 1500 rpm; 2 – PICE with TC at n = 1500 rpm and $n_{\text{тс}}$ = 46000 rpm; 3 – PICE with TC with intake system with leveling grid (n = 1500 rpm and $n_{\text{тс}}$ = 46000 rpm).

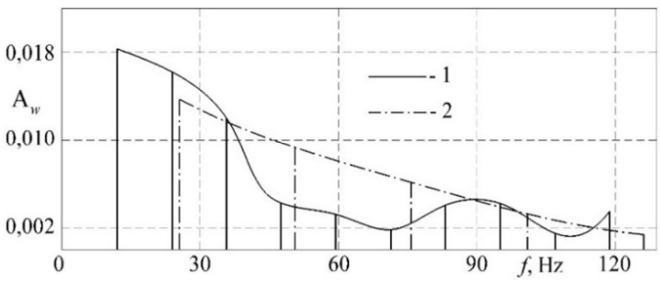

Figure 2. Spectrum amplitude graphs of the air flow velocity w_x in the intake system of engine with turbo-compressor (1) and without it (2) at n = 3000 rpm and $n_{\text{тс}}$ = 46000 rpm.

The installation of a turbo-compressor leads to a significant change in the flow structure in the intake system (figure 2). First, the values of significant frequencies of pulsation amplitudes of the air flow velocity change. The values of significant frequencies for an atmospheric PICE: 25.5 Hz, 50.6 Hz, 75.7 Hz, etc. (multiplicity – 25.1). Frequency values for a turbocharged PICE: 12 Hz, 24 Hz, 36 Hz, etc. (multiplicity – 12). Second, the regularity of amplitudes of the spectrum of the function $w_x = f(\tau)$ changes. In one case, the pattern is linear, in the other - complex, curvilinear. The spectrum amplitude graphs of the air flow velocity in the intake system of the PICE without turbo-compressor is almost linear (figure 2). The installation of a turbo-compressor leads to the appearance of a significant frequency in the region of 12 Hz, as well as to a more complex form of the function $A_w(f)$.

Spectrum amplitude graphs of the air flow velocity in the intake system of the PICE with a TC for different modes of turbo-compressor are shown in figure 3. It can be seen in figure 3 that the rotational speed of the turbo-compressor rotor has a noticeable effect on the structure of the air flow in the hydraulic system of a PICE. At the same time, it can be noted that significant amplitudes of the pulsation frequencies have the same frequencies for all values of $n_{\text{тс}}$: 12.1 Hz, 22.8 Hz, 33.5 Hz, 44.2 Hz etc. up to 150 Hz. The multiplicity of significant frequencies is 10.7 Hz. The greatest differences in amplitudes of the air flow velocity pulsations are observed for the first three significant frequencies. The maximum value of differences can reach 33 %. This indicates that the turbulence level of the air flow in the hydraulic system depends on the operating modes of the PICE and the turbo-compressor. The increased turbulence of the flow can have a negative effect on the filling of the cylinder with air, since in this case the hydraulic resistance of the system increases. So, it is necessary to develop ways to stabilize the pulsating flows in the hydraulic system of an engine, which is especially important for PICE with TC.

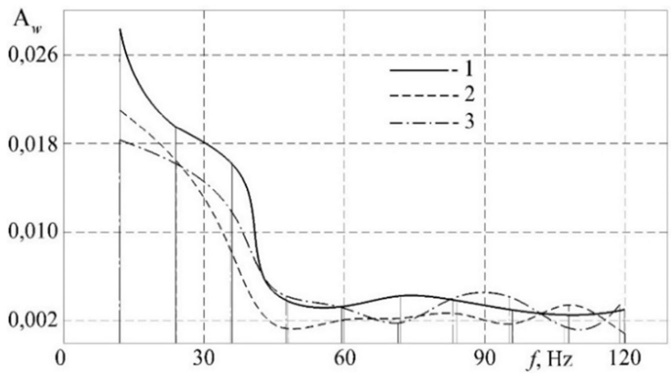

Figure 3. Spectrum amplitude graphs of the air flow velocity w_x in the intake system of a turbocharged engine at n = 3000 rpm and for different $n_{\text{тс}}$: 1 – $n_{\text{тс}}$ = 30000 rpm; 2 – 40000 rpm; 3 – 46000 rpm.

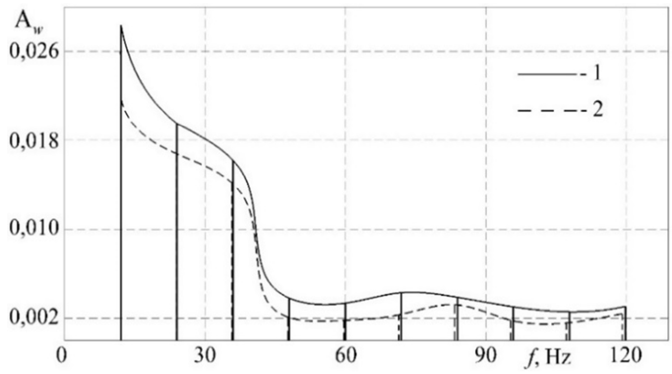

Figure 4. Spectrum amplitude graphs of the air flow velocity w_x in the base intake system (1) and in the intake system with leveling grid

(2) of turbocharged engines at n = 3000 rpm and $n_{\text{тс}}$ = 40000 rpm.

A leveling grid (based on the principle of honeycomb) was used as a method for stabilizing a pulsating air flow; it was installed in the output channel of the TC compressor in front of the engine intake duct. Spectrum amplitude graphs of the air flow velocity in the base intake system and in the hydraulic system with leveling grid are shown in figure 4. It can be seen from the figure that the installation of the leveling grid does not cause a change in the flow structure, since the form of the curve A_w (f) does not change. Also, significant frequencies and their multiplicity do not change. It should be noted that amplitudes of pulsations of the air flow velocity in the hydraulic system with a leveling grid are reduced on average by 15%. This indicates the stabilization of pulsating flows, which can lead to an improvement in the filling of the cylinder with air, as well as an increase in the reliability of parts and assemblies of the hydraulic system of the PICE with TC [18].

Spectrum amplitude graphs of the air flow pressure p_x in the intake system for different modes of turbo-compressor are shown in figure 5. It can be seen from figure 5 that for the investigated size of the engine and turbo-compressor, noticeable changes in the structure of the air flow are observed at TC rotor speeds above 46,000 rpm. In particular, it can be noted that the multiplicity of significant frequencies is reduced by 2 times (from 12 to 6 Hz) at $n_{\text{тс}}$ > 46000 rpm, as well as the amplitudes of pressure pulsations increase up to 40 % at frequencies not exceeding 30 Hz compared to the low speeds of the turbo-compressor rotor. According to the authors, this is due to the fact that the turbo-compressor has excessive performance in relation to the PICE at high $n_{\text{тс}}$ of the turbo-compressor rotor. As a result, reciprocating fluctuations in the air flow in the hydraulic system with a high degree of turbulence increase.

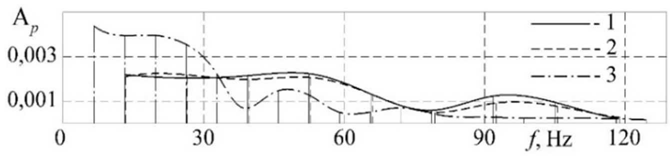

Figure 5. Spectrum amplitude graphs of the air flow pressure p_x in the intake system of a turbocharged engine at n = 1500 rpm and for different $n_{\text{тс}}$: 1 – $n_{\text{тс}}$ = 30000 rpm; 2 – 40000 rpm; 3 – 46000 rpm.

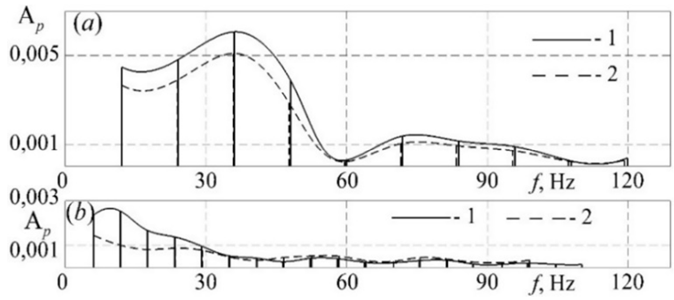

Figure 6. Spectrum amplitude graphs of the air flow pressure p_x in the basic intake system (1) and in the intake system with leveling grid (2) for PICEs with TC: a – n = 3000 rpm and $n_{\text{тс}}$ = 40000 rpm; b – n = = 600 rpm and $n_{\text{тс}}$ = 46000 rpm.

Spectrum amplitude graphs of the air flow pressure in the basic intake system and in the intake system with leveling grid for different operating modes of PICE and turbo-compressor are shown in figure 6. It can be seen that the installation of the grid does not cause changes in the amplitudes of significant frequencies and their multiplicity. Significant frequencies are: 12.1 Hz, 24.0 Hz, 36.1 Hz, etc. at n = 3000 rpm. And at n = 600 rpm significant frequencies are: 6 Hz, 11.9 Hz, 17.8 Hz, etc. The influence of n on the spectra of functions $w_x = f(\tau)$ and $p_x = f(\tau)$ is obvious. It can be noted that the amplitudes of the pressure pulsations of the air flow in the hydraulic system with a grid are reduced on average by 10-12%, which is typical of the frequencies of up to 60 Hz. The amplitudes of the pressure pulsations actually equalize at frequencies above 60 Hz for both cases. This indicates that the grid influences large-scale turbulence (minor fluctuations are retained in the flow). This indicates the equalization of the velocity field and pressure in the duct, which can lead to an improvement in filling the cylinder with air, as well as an improvement in the phenomena of mixing fuel and air and their subsequent ignition.

4. Conclusions

Based on the spectral analysis of the dependences $w_x = f(\tau)$ and $p_x = f(\tau)$ in the hydraulic system of the PICE (with and without turbo-compressor), the following opinions can be made:

- installation of a turbo-compressor leads to a significant change in the structure of gas flows in the intake system of the PICE: low-frequency (up to 45 %) and high-frequency (up to 25 %) amplitudes of velocity pulsations increase while maintaining the frequency multiplicity of significant frequencies;
- spectral analysis gave detailed information about the physical mechanisms of flows in different hydraulic systems;
- the magnitude of the turbo-compressor rotor speed has a major impact on the low-frequency (up to 50 Hz) amplitudes of velocity w_x and pressure p_x pulsations while maintaining the frequency multiplicity of significant frequencies;
- method for stabilizing the gas flow in the intake system of a PICE with turbo-compressor based on the principle of honeycomb has been proposed, which leads to a decrease in the low-frequency amplitudes of the w_x and p_x pulsations by up to 30%.

Data on the stabilization of pulsating air flows will improve the flow characteristics of the hydraulic system of PICEs with turbo-compressor, increase their reliability, as well as change the conditions for mixing fuel and air and their subsequent ignition.

Acknowledgments

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